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EXPLORING THE NATURE OF AUTOMATICITY IN TEXT PROCESSING

by

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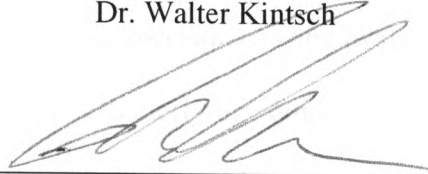
Exploring The Nature Of Automaticity In Text Processing

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Exploring The Nature Of Automaticity In Text Processing

Thesis directed by Dr. Walter Kintsch

A prevalent assumption in text comprehension research is that many aspects of text processing are automatic, with automaticity typically defined in terms of properties (e.g., speed, effort). The present research advocates conceptualization of automaticity in terms of underlying mechanisms and evaluates two such accounts, a *computational-efficiency* account (underlying computational processes become more efficient with practice) and a *memory-based processing* account (the underlying basis of processing shifts with practice, from computing interpretations to retrieving prior interpretations). In five experiments, short texts containing either an ambiguous or unambiguous syntactic structure were presented for multiple study trials. In both conditions, reading times in target regions decreased across trials, indicating automatization. Several findings supported the memory-based processing account (e.g., practice effects were largely item-specific, reading times were longer for ambiguous versus unambiguous sentences on early trials but converged on later trials). Some evidence was also found for a contribution of gains in computational efficiency (i.e., some item-general practice effects were observed). Implications for research on automaticity and text processing are discussed.

DEDICATION

To my mom.

ACKNOWLEDGMENTS

Sincere thanks to Walter Kintsch for his excellent support and guidance as my mentor. Thanks also to my other committee members Akira Miyake, Tim Curran, Lew Harvey, and Lise Menn, for their thoughtful comments and questions. And thanks to John Dunlosky, my best friend and critic.

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CHAPTER I

INTRODUCTION

Within the field of text processing research, a prevalent assumption is that text comprehension for skilled adult readers is heavily dependent upon automatic processing. Many of the specific processes underlying text comprehension are assumed to have automatic components, including lexical analysis (e.g., Brown, Gore, & Carr, 2002; Rayner & Frazier, 1989), syntactic and semantic parsing (e.g., Hahne & Friederici, 1999; Long, Seely, Oppy, & Golding, 1996), anaphor resolution (e.g., Greene, McKoon, & Ratcliff, 1992), and inferencing (e.g., Kintsch, 1993; McKoon & Ratcliff, 1992). Assumptions of automaticity are also manifest in general models of text comprehension (e.g., Just & Carpenter, 1980; Kintsch, 1998; Perfetti, 1988; Walczyk, 2000).

Given the ubiquity of assumptions about automatic processing in text comprehension research, an important question arises: What is meant by automaticity? Although appeal to automaticity is widespread, the definition of automaticity in text processing research is usually inconsistent or completely absent. Furthermore, scant research has directly investigated the nature of automaticity in text processing. This imbalance between the centrality of the notion of automaticity in theories of text processing on the one hand and the relative lack of conceptual consistency or direct empirical investigation on the other motivated the highest-level

goals of the present work: to advocate for clearer conceptualization of automaticity in theories of text processing and to stimulate discussion about the nature of automaticity within text processing. The present research is also intended to provide a first step in the empirical exploration of automaticity in text processing.

The Concept of Automaticity in Text Processing Research

Although the concept of automaticity is frequently invoked in research on text processing, the definition or description of automaticity is often completely absent. In those cases when a definition or description of automaticity is explicitly stated (or at least strongly implied), distinctions between automatic and non-automatic text processes involve assignments along observable or psychological dimensions, such as speed, effort, obligatory operation, autonomy, availability to awareness, extent of conscious control, attentional demands, or susceptibility to influence by contextual information or goals (e.g., Brown et al., 2002; Gernsbacher & Faust, 1995; Graesser, Hoffman, & Clark, 1980; Long et al., 1996; Lorch, 1998; McKoon & Ratcliff, 1992; Perfetti, 1993; Rayner & Frazier, 1989; Singer, Graesser, & Trabasso, 1994; Turner, Britton, Andraessen, & McCutchen, 1996; van den Broek, 1994).

One problem that arises from conceptualizing automaticity in terms of properties is that the subset of properties taken as necessary or sufficient to define automaticity often differs both within and between areas of research on specific text processes. To illustrate this point, Table 1 presents a sample of studies from the text processing literature in which properties are used to define or describe automaticity or to discriminate between automatic and non-automatic processes. As is evident upon

inspection of Table 1, very different sets of properties have been selected to describe automaticity (indeed, no two sets within this sample are the same), and some researchers have explicitly rejected properties that others have accepted as critical to the distinction between automatic and non-automatic processes.

Such inconsistency has several troublesome consequences. For one, it makes it difficult to compare theoretical claims about the relative involvement of automatic processing in text comprehension, either to competitively evaluate those claims or to identify ways in which theories may be aligned. Furthermore, to the extent that empirical work is designed to test for a particular property, those results may be of limited relevance to other theoretical accounts that do not identify that property with automaticity.

Inconsistency in the conceptualization of automaticity can also result in theoretical debates that are potentially unresolvable. For example, a recent and quite prominent debate within text processing research centered around the automaticity of inference processing during reading. As stated by McKoon and Ratcliff (1992), the issue of which inferences are formed automatically is "the most controversial point of debate between advocates of a minimalist position and advocates of a more constructionist view of text processing. There are many potential inferences that would be automatically generated during reading according to constructionist theories but not according to a minimalist view" (p. 441). At various points in their paper, McKoon and Ratcliff describe or define automatic inferences as occurring quickly ("in the first few hundred milliseconds of processing," p. 441), obligatorily, effortlessly, and without awareness. However, some advocates of the constructionist

Table 1.

A Sample of Text Processing Research Defining or Describing Automaticity in Terms of Properties.

Article	Property											
	C	O	S	R	A	At	Se	P	F	I	Aw	M
Brown et al. (2002)		Y			Y					Y		
Flores d'Arcais (1988)		Y		Y	Y						Y	Y
Gernsbacher & Faust (1995)		Y			Y	Y						
Hahne & Friederici (1999)	Y		Y	Y	Y	Y					Y	
Just & Carpenter (1980)			Y					Y	Y			
Kilborn & Friederici (1994)	Y		Y								Y	Y
Long et al. (1996)	Y		Y									
Lorch (1998)			Y	Y			Y					
McKoon & Ratcliff (1992)		Y,N	Y	N							Y	
Noveck & Posada (2003)		Y		Y								
Perfetti (1993)		Y	Y									
Singer et al. (1994)			N	N						Y	Y	
van den Broek (1994)	Y	Y	N	N								
Walczyk (2000)	Y		Y	Y		Y	Y	Y	Y	Y	N	Y

Note. Each of the columns represents a property that has been used by one or more researchers to define or describe automaticity or to differentiate automatic and non-automatic processes, where C = susceptibility to influence by conscious, strategic, or intentional control, O = obligatoriness, S = speed, R = resource or effort requirements, A = autonomy, At = attentional requirement, Se = selectivity, P = parallel or serial nature, F = flexibility, I = susceptibility to interference, Aw = openness to consciousness or awareness, and M = miscellaneous properties that were only listed once (including susceptibility to priming but not inhibition, error proneness, and resistance to modification). Y = explicitly used the property as a definitional or descriptive characteristic of automaticity. N = either explicitly rejected or questioned the utility of the property for discriminating between automatic and non-automatic processes.

view have rejected McKoon and Ratcliff's criteria for automaticity. For example, Singer et al. (1994) note that some automatic inferences are not necessarily obligatory. They also argued that some automatic inferences may be relatively slow to develop, citing evidence that one form of inference deemed automatic by McKoon and Ratcliff may take up to 1000 ms or more to complete. Singer et al. also argued against the automaticity of one class of inference identified by McKoon and Ratcliff based on evidence that the time course of these inferences can be influenced by the amount of distracting information in the context. However, these results could be dismissed by the minimalist account, given that McKoon and Ratcliff did not propose susceptibility to interference as a criterion for automaticity. On such grounds, the debate seems largely unresolvable.

Even if consensus could be achieved about the necessary and sufficient properties for defining automaticity, other concerns with the conceptualization of automaticity in terms of properties still exist. Of greatest concern, Logan and Klapp (1991) point out that "approaches that define automaticity in terms of manifest properties, such as speed, effortlessness, and autonomy (property-list approaches), are stipulative or descriptive but not predictive" (p. 179). Property-list approaches are typically silent on the question of why particular properties manifest with automaticity and which ones would be expected to manifest together. Additionally, as property-list approaches do not describe the nature of the underlying processes, they are limited in the extent to which they can explain how automatization takes place and conditions under which it is likely to develop. For instance, a limit of property-list approaches is apparent when the concept of automaticity is invoked to

account for individual differences in comprehension skill, both within healthy adult populations and between healthy adults and individuals with brain damage or disability (e.g., Kilborn & Friederici, 1994; Perfetti, 1988, Walczyk, 2000).

According to the Compensatory-Encoding Model, less skilled readers “possess subcomponents that are less automated” (Walczyk, 2000, p. 560), but that when given sufficient time, less skilled readers can use ‘compensatory behaviors’ to overcome deficiencies in automatic processes. In terms of the properties Walczyk (2000) identifies with automaticity (see Table 1), the text processes of less skilled readers would be predicted to be slower, more effortful, more susceptible to strategic control, require more attention, and would be more selective, serial, flexible, error prone, and susceptible to interference. Although demonstrating that higher skill readers and less skilled readers differed along each of these dimensions might be suggestive, it would still be unclear how the component processes of less skilled readers differ from those of high skill readers to give rise to these differences in manifest properties. Property-list approaches to individual differences in automaticity may also be limited in the extent to which they can predict which remedial activities would improve deficiencies and why they would be effective.

Process Accounts of Automaticity

In contrast to property-list accounts of automaticity, conceptualizing automaticity in terms of underlying processes (i.e., *process accounts* of automaticity) permits a greater degree of explanatory and predictive power. As Logan and Klapp (1991) argue, “theories that define automaticity in terms of underlying processes

allow us to deduce the properties of automaticity and explain why certain properties should appear together and others should not" (p. 192). Accordingly, the present research was intended to introduce an alternative to property-list approaches to defining automaticity in text processing, by importing process accounts from basic research on automaticity and evaluating them in the context of text processing. Exhaustive evaluation of all possible process accounts is beyond the scope of this paper. Instead, subsequent discussion focuses on a subset of contemporary theories of automaticity, in particular, those that illustrate process-based mechanisms that may be particularly useful for conceptualizing automaticity in the context of text processing. The goal of the present research is to evaluate the extent to which the particular process-based mechanisms suggested by these theories may play a role in automatization in text processing.

In drawing the distinction between property-list and process accounts of automaticity, note that the claim is not that properties are irrelevant to understanding automaticity. Process accounts of automaticity are designed to predict and explain the patterns of behavior that are often described by property-list accounts. Indeed, it is widely recognized that the "signature" pattern of automatization is a negatively accelerated speed-up in performance that accrues with practice, and process theories of automaticity must account for this robust finding to be considered viable.¹ Of importance here, different mechanisms have been proposed by process theories to account for the speed-up with practice.

¹ Typically, basic theories of automaticity are concerned not only with predicting the qualitative pattern associated with automaticity, but also with the quantitative aspects of the speed-up with practice (i.e., explaining the specific function). For present purposes, the function of the speed-up

Computational Efficiency

In its various formulations, the ACT Theory (e.g., Anderson, 1982, 1987, 1996; Anderson & Lebiere, 1998) has proposed several mechanisms that may underlie the effects of practice on task performance. For example, when an individual first starts to learn a skill, performance may depend primarily upon the use of domain-general interpretive procedures to learn from examples via analogy. This analogical processing of examples subsequently supports the generation of domain-specific procedures, or productions, for performing the task (referred to as *knowledge compilation*). One of the key processes involved in knowledge compilation is the combination of sequences of productions used to complete a task into one production that performs the same computation as the sequence but in fewer steps. Thus, knowledge compilation results in the generation of domain-specific productions that increase the speed of task performance by involving fewer computational steps.² Another key mechanism proposed in ACT to support faster task performance is *strengthening*. A production's strength is increased each time it is executed, provided

is not at issue. Interested readers may want to consult Logan (1988), Rickard (1997), and Palmeri (1999) for relevant discussion.

² It should be noted that the learning mechanisms described here are primarily taken from earlier formulations of the ACT Theory (e.g., ACT*, ACT-R 2.0). More recently, Anderson and Lebiere (1998) have proposed version ACT-R 4.0, which includes some tentative proposals for changes to the learning mechanisms introduced in earlier versions. For example, instead of knowledge composition and learning by analogy in its strictest sense, they propose instead a process called *production compilation*, in which the system "creates a goal to represent the dependencies in a particular problem-solving step. That is, it chooses, as a goal, to reflect on the problem solution. If this goal is successfully achieved and popped, a production will be compiled" (p. 110). The production compilation process involves creating variables for repeated terms, which creates a production that is more general than the example and thus subsequently can be applied to new items. Although production compilation differs from the other learning mechanisms in its computational specifics, presumably it achieves the same goals—to develop productions that are domain-specific but item-general and that will tend to include fewer steps than the original set of productions used to compute the interpretation (the characteristics important for present purposes).

it generates a correct result; the strength of a production is decreased when it returns an incorrect result. Thus, the strengthening process results in the functional pruning of any inappropriate productions created during knowledge compilation and the strengthening of those productions that turn out to be useful. Importantly, the strength of a production determines how quickly it will be executed on subsequent processing trials. "To an approximation, we may say that a production is automatic to the degree that it is strong" (Anderson, 1992, p. 170).

For present purposes, the important point is that the mechanisms in ACT outlined above provide a good example of how speed-ups with practice may arise from gains in *computational efficiency*, which come about either because the computation is completed in fewer steps (due to compilation) or because the computation is completed more rapidly (due to strengthening). Although gains in computational efficiency are not the only source of speed-up suggested by ACT, they are thought to play a prominent role in automatization.

Memory-based Processing

The Instance Theory of automaticity (Logan, 1988) proposes another mechanism that may underlie speed-ups with practice. According to Instance Theory, the interpretation of a stimulus is computed by algorithmic processes the first time the stimulus is encountered, and that interpretation is stored as an instance in long-term memory. Upon subsequent encounters of the stimulus, interpretation may either be computed again by the same algorithmic processes, or the previously computed interpretation may be retrieved from long-term memory. The Instance Theory

proposes that a race occurs between the algorithmic processes and retrieval, such that interpretation will be supported by whichever of the two processes is faster. With increasing exposures to the stimulus, an increasing number of instances will be stored, with a concomitant increase in the probability of an instance being retrieved quickly enough to finish before the algorithmic processes. When retrieval of previously computed interpretations becomes sufficiently quick and reliable, use of the presumably more costly algorithmic processing may be abandoned altogether. By this account, "Automaticity is memory retrieval: Performance is automatic when it is based on single-step direct-access retrieval of past solutions from memory" (Logan, 1988, p. 493).

The Component Power Laws Theory (or CMPL; Rickard, 1997) also proposes that memory-based processes support automatization, although the representational and processing assumptions of CMPL differ from Instance Theory in some respects. For example, CMPL assumes that prior interpretations of a particular stimulus are stored as a prototype rather than as separate instances, and that the strength of that prototype is incremented with subsequent encounters of the stimulus. Additionally, CMPL assumes that algorithm and retrieval do not race, but rather that only one of the two processes will initially be engaged on any processing trial (although the other may be executed if the process that is initially engaged fails). However, CMPL agrees with the basic claims of Instance Theory that are relevant for present purposes: First, automatization reflects a decreasing reliance on computational processes and an increasing reliance on memory-based processes. Second, what is retrieved from memory is information about prior interpretations of particular stimuli.

Attention-based Mechanisms

The current research was designed to evaluate the potential contributions of two mechanisms to automaticity in text processing: computational efficiency as described by ACT and memory-based processing as proposed by Instance Theory and CMPL. However, brief mention of one other kind of mechanism that has been proposed to underlie automaticity is in order. Specifically, several process accounts can be loosely grouped as proposing attention-based mechanisms of automaticity, based on the general claim that performance may speed up with practice as individuals learn to attend to only task-relevant information. For example, Haider and Frensch (1996) proposed the information reduction hypothesis, according to which “people learn, over the course of practice, to separate task-relevant from task-redundant information and to limit their processing to relevant aspects of the task...changes in RT patterns across practice (i.e., power law of practice) may at least partially reflect systematic reductions in the amount of information that is processed, rather than changes in the efficiency with which task components can be performed” (p. 306). Haider and Frensch (1999) suggested that after enough practice to allow discrimination between relevant and irrelevant task information, individuals intentionally select only relevant information and ignore other information. Research by Schneider and his colleagues (e.g., Schneider & Shiffrin, 1977; Schneider, Dumais, & Shiffrin, 1984; Schneider & Chein, 2003) has demonstrated that attentional biases for task-relevant information and against distracting information can also develop via low-level, non-intentional processes, given extended practice

under consistent training conditions. However, the extent to which either of these attentional mechanisms contributes to automaticity in text processing may be minimal. Most text processing situations will require the processing of all of the content within a text (e.g., most texts are unlikely to include information that is completely irrelevant to the topic or purposefully distracting). Accordingly, the present research does not attempt to evaluate attention-based mechanisms of automaticity.

Evaluating Process Accounts of Automaticity in Text Processing

As outlined above, the basic theoretical work on automaticity suggests at least two mechanisms that may underlie automaticity in text processing, computational efficiency as described by ACT and memory-based processing as proposed by Instance Theory and CMPL.³

It is important to note that these are not mutually exclusive mechanisms. Both may play a role, although it is not a foregone conclusion that both of them will. One point of agreement among researchers on automaticity is that a mechanism that plays a primary role in automatization within one domain may contribute minimally in other task domains (e.g., Blessing & Anderson, 1996; Haider & Frensch, 1996; Logan, 1988; Rickard, 1997). Each of the proposed mechanisms has found empirical support in other task domains, but they have not been directly investigated in text processing. Thus, the present research was designed to provide initial evidence for the

³ For the sake of brevity, the terms “computational efficiency” and “memory-based processing” will be used subsequently without continued referencing of the particular theories from which they have been derived (ACT and Instance Theory and CMPL, respectively). However, the use of these terms is still intended to refer to the mechanisms as described by these particular theories.

role that either or both of these mechanisms may have in text processing.

To explore the computational efficiency and memory-based accounts of automaticity in the context of text processing, the present research adapted the most prevalently used experimental strategy in basic research on automaticity. Specifically, changes in performance of one component text processes (syntactic analysis) were examined across multiple experimental trials. Participants read short texts with target sentences that contained either an ambiguous or unambiguous syntactic structure. To illustrate, a sentence that begins “The doctor called...” is temporarily ambiguous syntactically, because the sentence may continue with “called” as a main verb (e.g., “The doctor called the nurse over to help with a patient”) or in a subordinate clause (e.g., “The doctor called frantically by the patient rushed into the room”).

Previous research has shown that at the point of ambiguity, readers typically adopt a main verb interpretation (e.g., Britt, Perfetti, Garrod, & Rayner, 1992; Ferreira & Clifton, 1986).⁴ When subsequent information disambiguates in favor of a subordinate clause interpretation (as in the present materials), *reanalysis* is necessary to correct the initial misinterpretation. The need for reanalysis can be avoided by explicitly marking the role of the verb in the subordinate clause (e.g., “The doctor *that was* called frantically by the patient rushed into the room”), as in the unambiguous text versions used here. Thus, although arriving at an appropriate interpretation of both ambiguous and unambiguous sentences will involve computation upon initial encounter, ultimate interpretation of ambiguous sentences

⁴ Main verb interpretations are not favored in all circumstances. With strong contextual support, readers can initially adopt a relative clause interpretation (e.g., Sedivy, 2002). Given the purpose of the present research, however, encouraging relative clause interpretation would be disadvantageous and thus neutral contexts were used.

will typically require additional computation for reanalysis.

The interesting (and heretofore unexamined) issue concerns how ambiguous and unambiguous sentences are processed on subsequent reading trials. For both kinds of sentence, the computational efficiency and memory-based processing accounts both predict a negatively accelerated speed-up in processing times with practice, which is the signature pattern of automatization. Indeed, speed-up with practice is the key finding that the theories described above were designed to explain. However, additional predictions follow from the particular mechanisms hypothesized to underlie speed-ups with practice.

The memory-based processing account makes two further predictions. According to this account, automatization reflects the retrieval of previously computed interpretations for particular stimuli. Thus, the key prediction of this account is that gains in processing speed will be limited to the particular sentences processed on previous trials (or more generally, to those for which relevant prior interpretations are available to be retrieved) and will not generalize to new sentences of similar structure. The memory-based processing account also makes a secondary prediction: although processing times will be greater for ambiguous sentences than for unambiguous sentences on initial reading trials, processing times for the two kinds of sentence will not differ on later reading trials. This prediction follows from the idea that interpretation on initial trials will be based on computation (which requires more time for ambiguous sentences due to reanalysis), whereas later trials will be based on retrieval of previously computed interpretations (which should not differ for ambiguous and unambiguous sentences). This prediction is consistent with findings

reported by Logan and Klapp (1991) from an alphabet arithmetic task (e.g., $A + 4 = E$). In initial trials, response times increased linearly as the digit addend increased, presumably reflecting computation of the solution by counting up through the alphabet. In later trials, reaction time did not significantly vary with digit magnitude, presumably because responses were based on retrieval of prior solutions.

In addition to a speed-up with practice, the computational efficiency account makes two further predictions. According to this account, practice improves the efficiency with which the productions underlying performance are carried out, because increasingly fewer steps are involved in the computation (due to knowledge compilation) and because the compiled productions then strengthen with practice. Importantly, knowledge compilation “creates productions that encode the sequence of general productions for a task, but the composed productions are still general” (Anderson, 1982, p. 389), because they typically include variables that can be filled by the features of different stimuli rather than stimuli-specific constants. Accordingly, a key prediction of the computational efficiency account is that speed-ups with practice will not be limited to repeated sentences but will also accrue to new sentences of similar structure (or more generally, to those sentences involving the same productions for the computation of their interpretation).

A secondary prediction of the computational efficiency account concerns the extent to which processing times for ambiguous and unambiguous sentences will converge across reading trials. The most straightforward prediction of this account is that although processing times for ambiguous sentences may approach those for unambiguous sentences, complete convergence (i.e., 0 ms difference between the two

conditions) will not be observed. Processing of both kinds of sentence will presumably benefit from more efficient analysis procedures, and ambiguous sentences will further benefit from more efficient reanalysis procedures (recall that reanalysis is seldom if ever involved in processing unambiguous sentences). However, interpretation of ambiguous sentences will continue to require the execution of more productions (due to reanalysis). According to ACT, the amount of time required to complete a task depends on the number of productions that must be computed, given that they are executed serially and require a minimum of 50 ms to run (Anderson & Lebiere, 1998). Thus, although the difference in processing times for ambiguous and unambiguous sentences may diminish with practice, a non-zero difference is still predicted for all processing trials.

CHAPTER II

EXPERIMENT 1

Method

Materials and Procedure

Materials included 18 short narrative texts (M words = 74, M sentences = 5.4), nine of which were critical texts and nine of which were filler texts. Each critical text contained a target sentence with a subordinate clause. Two versions of each target sentence were written. In the ambiguous condition, the subordinate clause was unmarked (e.g., “The animal curled up in the basket sprang into action suddenly”). In the unambiguous condition, the subordinate clause was explicitly marked (e.g., “The animal *that was* curled up...”). A sample critical text is presented in Table 2. As a cover task, participants were told that the experiment was intended to investigate the effects of rereading on text learning, and thus filler texts were used for the alleged single-trial condition. The inclusion of filler texts also further reduced the proportion of text sentences containing an unmarked subordinate clause across all texts presented.

Table 2.

Sample Critical Text from Experiment 1

Harry had driven taxis for many years but he still really enjoyed it. Today there was all kinds of excitement. His first call involved a pregnant woman who needed to get to the hospital and at one moment he expected to have to deliver the baby himself. He then had to take a special package to the airport and just arrived in time. On the way back he turned on his radio. *They said that a woman [who was] rushed to the hospital had given birth safely.* Harry felt that he had done a good job that day.

Note. The critical sentence appears in italics. The bracketed words appeared in the unambiguous version of the critical sentence and did not appear in the ambiguous version (neither italics nor brackets were presented to participants).

The disambiguating region of each target sentence consisted of 1-3 words and contained the main verb of the sentence (e.g., “They said that a woman [who was] rushed to the hospital *had given birth* safely”). To collect reading times in the disambiguating regions, texts were presented via moving window: Each text was presented one segment (1-5 words) at a time for self-paced study. The first segment was presented in the upper left of the computer screen. When the participant pressed the spacebar, each of the characters of the first segment was replaced with dashes and the next segment was presented to the right of the first. Each subsequent segment was presented in the same manner until the end of the text. Participants were not

permitted to move backward to reread previously viewed segments.

One filler text was presented during instructions to illustrate the moving window method to participants. Additionally, the first two texts presented during experimental trials were filler texts to allow further practice with the moving window before encountering a critical text. Eight randomly selected critical texts and the remaining six filler texts were then presented in random order. For each participant, four of these critical texts contained ambiguous target sentences and four contained unambiguous sentences (i.e., a given participant saw only one version of each critical sentence). Each filler text was presented for one study trial. Each of the eight critical texts was presented for four consecutive study trials. The ninth critical text was presented once during the last experimental trial and always contained an ambiguous target sentence.

To encourage participants to read carefully, two comprehension questions were administered after the final study trial of each text. Each question asked whether a short statement about the text was true or false.

Participants and Design

Fifty-three University of Colorado undergraduates participated for course credit in Introductory Psychology. Data from one participant who failed to follow directions (as evidenced by near-chance performance on the comprehension questions) were excluded from analysis. The two within-subject variables were Sentence Type (ambiguous or unambiguous) and Study Trial (1-4).

Results and Discussion

Of greatest interest are reading times in the region of target sentences containing disambiguating information, as reanalysis typically takes place within this region (e.g., Britt et al., 1992). Figure 1 shows mean reading times (in msec) for disambiguating regions in the two conditions on each study trial.⁵ The signature pattern of automatization is evident in both conditions: Reading times decreased across trials, with gains greatest on early trials and diminishing thereafter. A repeated measures analysis of variance (ANOVA) yielded significant main effects of study trial [$F(3,153) = 119.76$, $MSe = 37718.67$, $p < .001$] and sentence type [$F(1,51) = 10.61$, $MSe = 87856.27$, $p = .002$], and a significant interaction [$F(3,153) = 6.76$, $MSe = 26347.69$, $p < .001$].⁶ Thus, the speed-up with practice predicted by both the computational efficiency and memory-based processing accounts obtained.

Figure 1 also shows the data relevant for evaluating the secondary predictions of the computational efficiency and memory-based processing accounts. Reading times were greater in the ambiguous condition than in the unambiguous condition

⁵ In addition to the raw reading times reported in each experiment, a second series of analyses was conducted on residual reading times to control for region length (for an explanation of and motivation for residual reading time analyses, see Trueswell, Tanenhaus, & Garnsey, 1994, Appendix B). For each participant, one regression analysis was performed for each reading trial (i.e., 4-10 regression analyses per participant, depending upon experiment). In each regression, the participant's reading times for each region of the critical texts (i.e., all regions for all sentences of all critical texts) were predicted by the number of characters in each region. For each participant, the intercept and slope from each regression was then used to compute predicted reading times for the particular regions of interest in each experiment. Analyses were then performed across individual mean residual reading times (i.e., the difference between predicted and actual reading times within a critical region). In all comparisons of interest, analyses on raw reading times and on residual reading times yielded the same pattern of results.

⁶ Analyses reported are conducted over subjects; the nature of the experimental design employed obviates the need for item analyses (Raaijmakers, Schrijnemakers, & Gremmen, 1999).

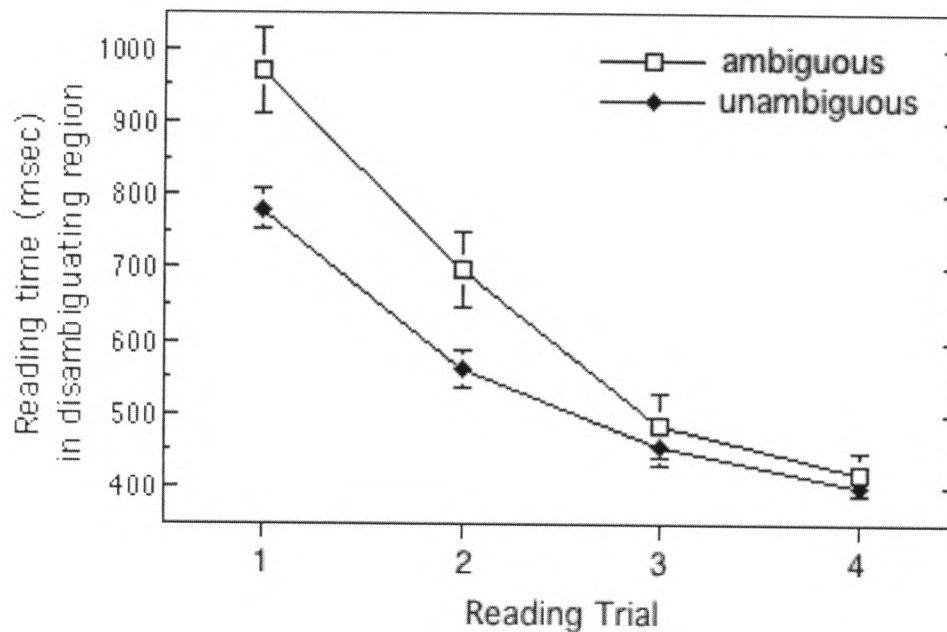


Figure 1. Mean reading times (in msec) for the disambiguation region of ambiguous and unambiguous versions of the target sentences, for each reading trial in Experiment 1. Error bars represent *SEMs*.

during the first and second study trials [$t(51) = 3.68, p < .01$, and $t(51) = 3.20, p < .01$] but then did not significantly differ on the remaining trials ($ts < 0.90$). The non-significant difference in processing times on Trial 4 is most consistent with the prediction of the memory-based processing account.

More conclusive evidence for the two accounts is provided in Figure 2, which plots mean reading time across participants for the disambiguating region of ambiguous sentences for each of the 17 trials in which an ambiguous sentence was processed (recall that the first four ambiguous texts were each read four times and the final ambiguous text was read once). Consider first the prediction of the computational efficiency account, according to which speed-ups with practice will be

item-general. To the extent that speed-ups with practice are only due to increased efficiency of item-general productions, one would expect to observe a monotonic decrease in reading times across the 17 trials, but this is clearly not the case. Instead, the scalloped pattern indicates strong item-specific effects of practice that conform to the prediction of the memory-based processing account. Collapsing across repeated texts, processing times were significantly faster on Trial 4 than on Trial 1, $t(51) = 10.65, p < .01$. Additionally, processing times on Trial 4 were significantly faster than processing time for the new ambiguous text presented on the last experimental trial, $t(51) = 6.21, p < .01$.

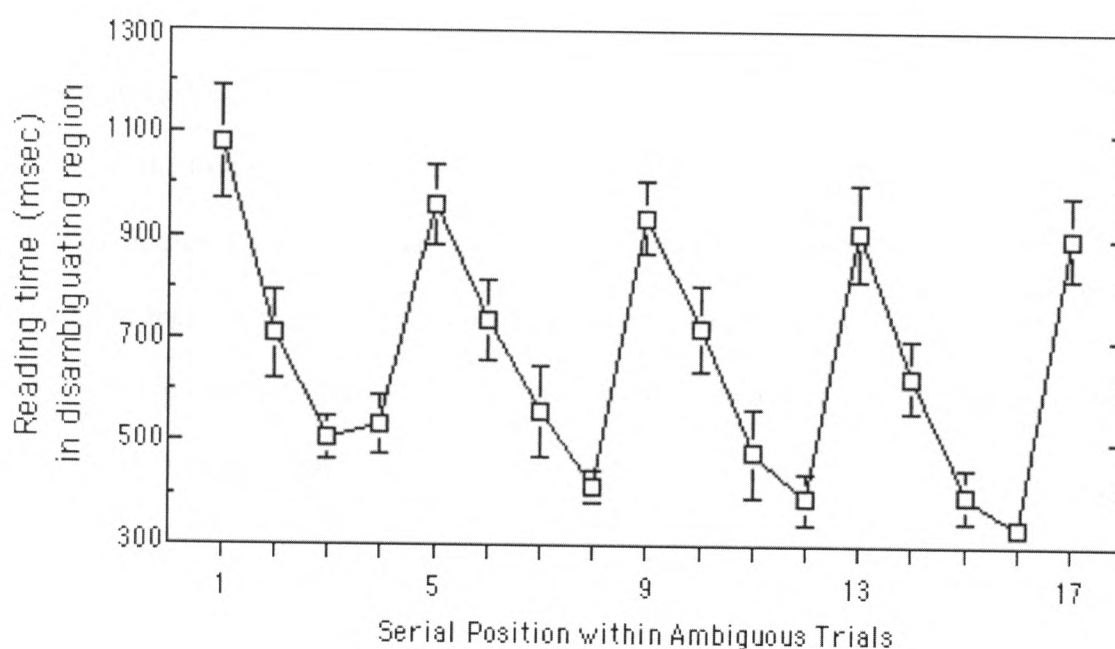


Figure 2. Mean reading times (in msec) for the disambiguation region of ambiguous sentences for each trial in which an ambiguous sentence was presented in Experiment 1. Error bars represent *SEMs*.

However, the results also show some evidence for item-general practice effects, suggesting that computational efficiency may also be contributing to the observed speed-ups. Specifically, although previously computed interpretations may be retrieved on later encounters of particular stimuli, the memory-based processing account states that analysis of stimuli depends upon computation on initial encounters. Computation on these trials could become more efficient with each next initial encounter of a stimulus. That is, although computation may not underlie performance on all trials, when interpretation does rely on computation (e.g., initial encounters of stimuli), computational efficiency will improve with practice across those trials. Thus, although reading times did not decrease monotonically across *all* encounters of ambiguous sentences, a monotonic decrease across *initial* encounters of ambiguous sentences would provide some evidence for the computational efficiency account. Indeed, there does appear to be a negatively accelerated speed-up across initial study trials (i.e., the first study trial for each ambiguous sentence; serial positions 1, 5, 9, 13, and 17 in Figure 2). When the data are plotted in logarithmic coordinates (see Logan, 1988), the negative slope from the linear regression over first study trials is significant ($-.98, p < .05$), suggesting some improvement in the efficiency of the productions involved in computing interpretations of ambiguous sentences.

CHAPTER III

EXPERIMENT 2

In support of the memory-based processing account, Experiment 1 demonstrated substantial item-specific decreases in reading times across trials, as well as elevated reading times for ambiguous sentences on initial trials but then non-significant differences in reading times for ambiguous and unambiguous sentences by Trial 4. Although these patterns are consistent with the idea that processing shifted from computation to retrieval of previous interpretations by Trial 4, they could also be due to participants “skimming” or superficially processing the text on later trials in both conditions (e.g., due to boredom). That is, the drastic item-specific decreases in reading time may not reflect faster processing of repeated items but the absence of processing of the repeated items. Similarly, the convergence of reading times in the ambiguous and unambiguous conditions by Trial 4 was attributed to processing in both conditions being supported by the same underlying process (i.e., memory-based retrieval of prior interpretations), but it could reflect participants skimming or even skipping through the text in both conditions. Experiment 2 tested this alternative explanation by semantically altering a phrase after the disambiguating region of target sentences in four of the critical texts (two ambiguous and two unambiguous) during the fourth study trial (e.g., “The animal [that was] curled up in the basket sprang *into action* suddenly” was changed to “The animal [that was] curled up in the basket

sprang *over her head* suddenly” on the fourth trial; this region is referred to as the “critical region” hereafter). To the extent that participants are advancing through texts without processing them on Trial 4, reading times in the critical region of altered and unaltered sentences will not differ.

The results of Experiment 1 also provided some support for the computational efficiency account, in that reading times for initial encounters of ambiguous sentences decreased significantly across the experiment. Much of this decrease was localized to the difference between the first and second ambiguous sentences (i.e., serial positions 1 and 5 in Figure 2), with minimal gains in processing speed thereafter. One concern is that the early decrease in reading times may have at least partly reflected the effects of practice on advancing the moving window rather than the effects of practice on computational parsing processes. That is, reading times for the first ambiguous sentence may have been elevated because participants were not sufficiently comfortable advancing the moving window and thus were slower overall to forward the window on early trials. Experiment 2 addressed this concern by presenting the first filler text for four study trials, to give participants more practice advancing the moving window prior to encounter of the first critical text.

Method

Thirty-four University of Colorado undergraduates participated for course credit in Introductory Psychology. The procedure was the same as in Experiment 1 except for the two modifications just described.

Results and Discussion

Figure 3 shows mean reading times (in msec) for disambiguating regions of target sentences. A repeated measures ANOVA yielded significant main effects of study trial [$F(3,99) = 46.56$, $MSe = 34383.53$, $p < .001$] and sentence type [$F(1,33) = 14.94$, $MSe = 40831.81$, $p < .001$], and a significant interaction [$F(3,99) = 6.11$, $MSe = 17438.98$, $p = .001$]. As in Experiment 1, reading times were greater in the ambiguous condition than in the unambiguous condition during the first and second study trials [$t(33) = 4.57$, $p < .01$, and $t(33) = 2.04$, $p < .01$]. Furthermore, this difference was only marginal on Trial 3 and was not significant on Trial 4 [$t(33) =$

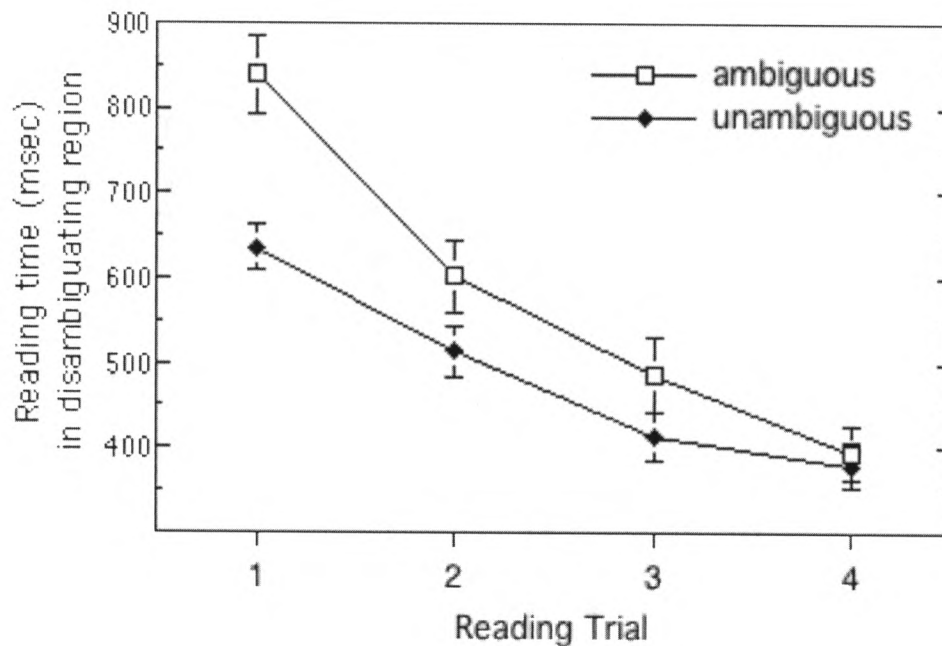


Figure 3. Mean reading times (in msec) for the disambiguation region of ambiguous and unambiguous versions of the target sentences, for each reading trial in Experiment 2. Error bars represent *SEMs*.

2.02, $p < .06$, and $t(33) = 0.80$]. Figure 4 plots mean reading times for the disambiguating region in the 17 trials in which an ambiguous sentence was processed. As in Experiment 1, strong item-specific effects of practice were observed, with processing times on Trial 4 significantly faster than on Trial 1, $t(33) = 8.80$, $p < .01$, and significantly faster than processing time for the new ambiguous text presented on the last experimental trial, $t(33) = 5.28$, $p < .01$. Thus, Experiment 2 provides a replication of the key patterns supporting the memory-based processing account.

Evidence that these patterns were not due to superficial processing comes from examination of reading times in the critical region of altered and unaltered sentences. Mean reading times (in msec) on each study trial are plotted in Figure 5

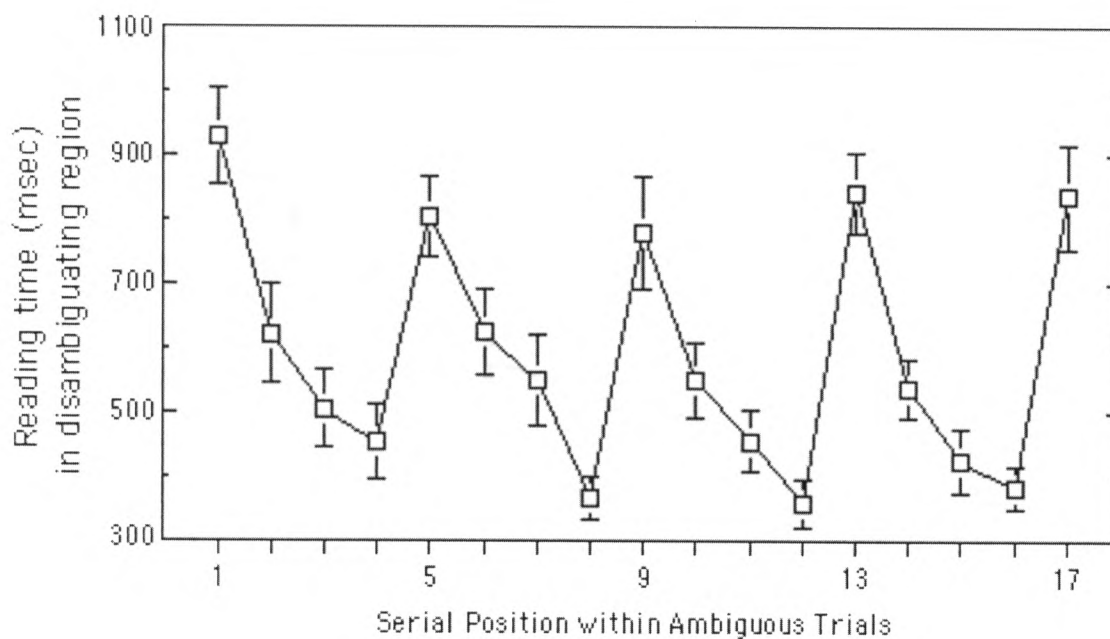


Figure 4. Mean reading times (in msec) for the disambiguation region of ambiguous sentences for each trial in which an ambiguous sentence was presented in Experiment 2. Error bars represent SEMs.

(results in this region did not differ for ambiguous and unambiguous sentences and are thus collapsed across this variable). A repeated measures ANOVA yielded significant main effects of study trial [$F(1,33) = 8.63$, $MSe = 123498.22$, $p = .006$] and sentence type [$F(3,99) = 11.47$, $MSe = 170983.43$, $p < .001$], and a significant interaction [$F(3,99) = 11.71$, $MSe = 114373.28$, $p < .001$]. Importantly, whereas reading times in the critical region did not significantly differ on Trials 1-3 ($ts < 1.31$), reading times on Trial 4 were significantly greater when the target sentence had been altered than when it had not, $t(33) = 3.67$, $p < .01$. These results suggest that participants were still processing the texts even after multiple study trials.

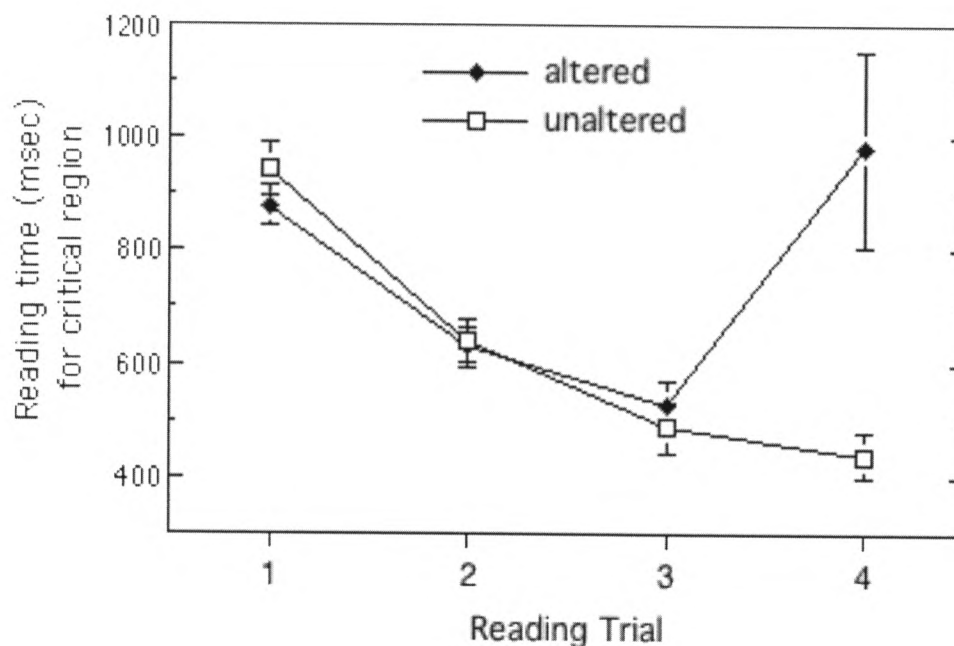


Figure 5. Mean reading times (in msec) for the critical region in altered and unaltered sentence conditions, for each reading trial in Experiment 2. Error bars represent SEMs.

With respect to evaluating the potential contribution of computational efficiency, the slope from the linear regression over first study trials (serial positions 1, 5, 9, 13, and 17 in Figure 4) when the data are plotted in logarithmic coordinates was negative but not significant ($-.58, p > .30$). Although the trend was consistent with the computational efficiency account, the decrease across first trials observed in Experiment 1 may have been due at least in part to insufficient practice with the experimental method rather than to an improvement in the efficiency of parsing processes.

CHAPTER IV

EXPERIMENT 3

Experiment 2 provided evidence that the item-specific speed-up with practice and the convergence of processing times for ambiguous and unambiguous sentences is not due to participants superficially processing the texts on later reading trials. However, Experiment 2 does not conclusively demonstrate that readers are still *syntactically* processing the texts on later reading trials. The alterations made to the critical sentences in Experiment 2 could have been detected if lexical processing was sensitive to the relative familiarity of repeated words versus the newly introduced content words. Similarly, the alterations in the critical sentences could have been detected if semantic processes were sensitive to the introduction of new idea units. The important point is that readers would not necessarily have to process the texts syntactically to detect the alterations that were made.

Experiment 3 was designed to provide stronger evidence that readers process texts syntactically on later reading trials, to support the claim the pattern of results taken to support the memory-based processing account is due to the automatization of syntactic processing rather than to the absence of syntactic processing. Specifically, 2-3 function words were inserted into each ambiguous sentence on Trial 4 to change the syntactic structure, such that the appropriate interpretation of the ambiguous verb changed from subordinate clause to main verb (e.g., "The troops dropped from the

plane could overshoot the target” was changed to “The troops dropped from the plane *and so they* could overshoot the target” on the fourth trial). Importantly, the exact same content words were used in both versions, and the meaning of the sentence was preserved (e.g., in both syntactic structures, troops drop from a plane and run the risk of missing a target). Thus, syntactic processing is necessary to detect the alterations. If readers are no longer processing texts syntactically on the fourth trial, reading times will not differ for altered versus unaltered sentences.

In contrast, the memory-based processing account predicts that reading times will be longer for altered versus unaltered sentences on Trial 4. The logic of this prediction is as follows: According to this account, the syntactic interpretation adopted on Trial 4 is based on the retrieval of prior interpretations. On prior encounters, reanalysis processes will presumably have corrected initial misinterpretations and thus subordinate clause interpretations of the ambiguous verbs will have been stored. Thus, subordinate clause interpretations will be retrieved and adopted, but this interpretation will now be incorrect on Trial 4. Reanalysis will then be required, and hence an elevation in reading times is predicted.

Method

Fifty-five University of Colorado undergraduates participated for course credit in Introductory Psychology. Data from two participants who failed to follow directions were excluded from subsequent analyses. The procedure was the same as in Experiment 2 except for the modification to the materials used on Trial 4 described above.

Results and Discussion

The top panel of Figure 6 shows mean reading times (in msec) for disambiguating regions of target sentences. A repeated measures ANOVA yielded significant main effects of study trial [$F(1,52) = 33.77$, $MSe = 50392.23$, $p < .001$] and sentence type [$F(3,156) = 55.53$, $MSe = 32166.29$, $p < .001$]. The interaction was not significant, $F(3,156) = 1.64$. Reading times were greater in the ambiguous condition than in the unambiguous condition during the first three study trials [$t(52) = 3.77$, $p < .01$, $t(52) = 4.24$, $p < .01$, and $t(52) = 2.30$, $p < .05$]. The most important result here concerns reading times during Trial 4. In contrast to Experiments 1 and 2 in which the syntactic structure of ambiguous sentences was preserved on all study trials, reading times for ambiguous and unambiguous sentences did not continue to converge on Trial 4. Instead, reading times for ambiguous sentences significantly diverged from reading times for unambiguous sentences, $t(52) = 3.88$, $p < .01$, as predicted by the memory-based processing account.

As is evident from inspection of the bottom panel of Figure 6, the disruption in syntactic processing of the ambiguous sentences caused by alterations to syntactic structure carried over into the next processing region (referred to as the “spillover region”). A repeated measures ANOVA on reading times in the spillover region yielded significant main effects of study trial [$F(1,52) = 6.87$, $MSe = 58314.68$, $p < .02$] and sentence type [$F(3,156) = 83.05$, $MSe = 46203.78$, $p < .001$], and a significant interaction [$F(3,156) = 4.04$, $MSe = 27256.29$, $p < .01$]. Most important, reading times were significantly longer for ambiguous sentences than for

unambiguous sentences on Trial 4, $t(52) = 2.91, p < .01$.

One might argue that it is not particularly surprising that changing a sentence that has appeared three times previously may surprise a reader and cause a disruption.

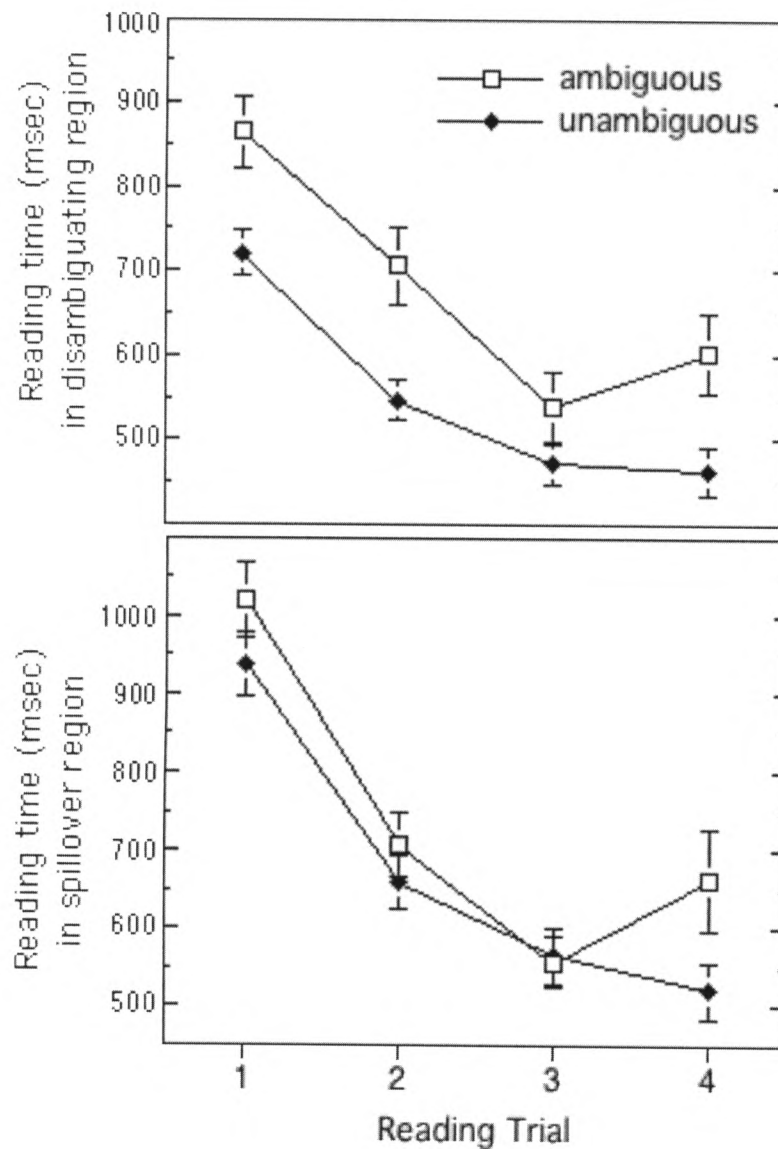


Figure 6. Mean reading times (in msec) for the disambiguation region (top panel) and spillover region (bottom panel) of ambiguous and unambiguous versions of the target sentences, for each reading trial in Experiment 3. Error bars represent *SEMs*.

However, the important point to note is that in order for the reader to have been surprised, s/he must have detected the change. Furthermore, in order for the change to have been detected, syntactic processes must have been operating, because only the syntactic structure of the sentence was changed on Trial 4. Thus, taken together, the results across the disambiguating and spillover regions suggest that participants were still engaging in syntactic processing of the texts even after multiple trials.

Mean reading times for the disambiguating region in the 17 trials in which an ambiguous sentence was processed are plotted in Figure 7. With respect to evaluating the potential contribution of computational efficiency, the negative slope from the

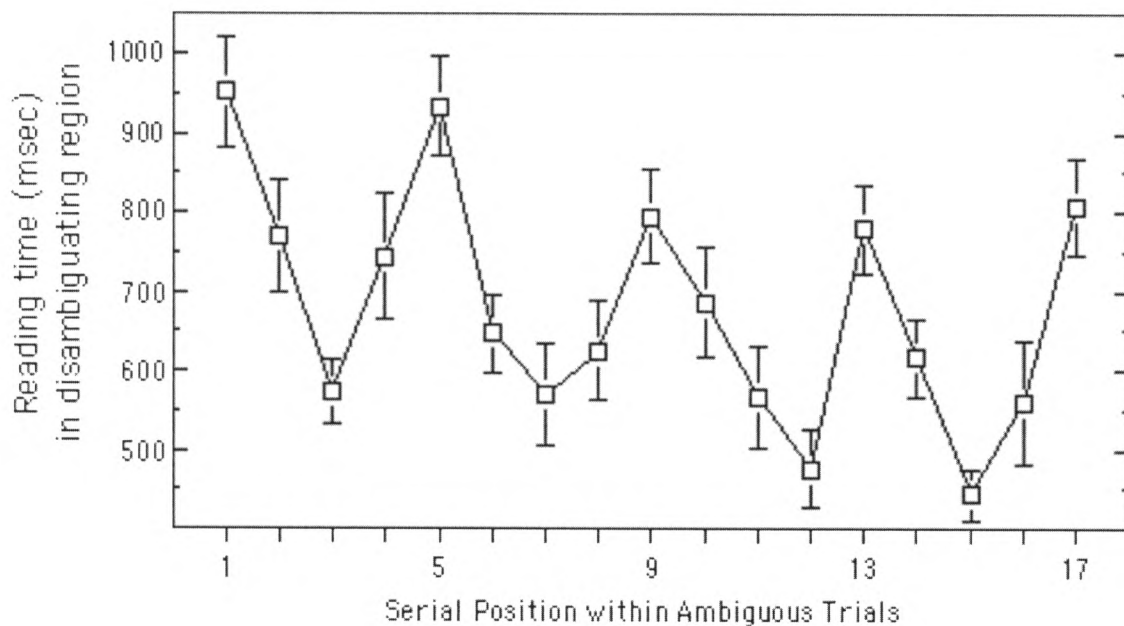


Figure 7. Mean reading times (in msec) for the disambiguation region of ambiguous sentences for each trial in which an ambiguous sentence was presented in Experiment 3. Error bars represent *SEMs*.

linear regression over first study trials when the data are plotted in logarithmic coordinates was significant ($-.88, p < .05$). Given that participants received more practice with the moving window prior to encounter of the first ambiguous sentence, this trend may reflect an improvement in the computational efficiency of syntactic reanalysis.

CHAPTER V

EXPERIMENT 4

Overall, the results of Experiments 1-3 are consistent with the claim of the memory-based processing account that on later encounters of repeated stimuli, readers are retrieving stored prior interpretations of syntactic structures rather than computing syntactic interpretations anew. The most conclusive evidence comes from the item-specific effects observed in Figures 2, 5, and 7. One might argue that the substantial item-specific practice effects that accrued to repeated items may reflect repetition priming rather than retrieval of prior interpretations from long-term memory, given that the texts were repeated in massed fashion. In response to this specific concern, several researchers have argued that repetition priming and automaticity or skill learning reflect the same underlying mechanism (e.g., Logan, 1990; Gupta & Cohen, 2002), in which case this argument poses no interpretive difficulty for present purposes. Nonetheless, the concern taps a more general issue—namely, whether the item-specific effects are due to relatively temporary maintenance of activation, rather than to learning of a more stable database that could support subsequent processing. If so, then the support for a potential role of memory-based processing in the automatization of text comprehension would be weakened. To eliminate the concern that the item-specific practice effects were due to temporary

maintenance of activation, presentations of the repeated texts were distributed rather than massed in Experiment 4.

Note that the issue of temporary activation is of less relevance to the computational efficiency account, given that the evidence for item-general effects was obtained with intervening material between encounters of novel stimuli. However, the computational efficiency account could also profit from more evidence in its favor, considering that the evidence for item-general speed-ups with practice were somewhat inconsistent (i.e., significant in Experiments 1 and 3 but not in Experiment 2). One potential limitation of Experiments 1-3 is that they included relatively few novel stimuli. Accordingly, the number of stimuli used in Experiment 4 was increased, to allow examination of the pattern across more trials.

Method

Materials and Procedure

Materials and procedure were the same as in Experiments 1-3 with some important exceptions. Materials included 72 short narrative texts (including the 18 used in Experiments 1-3), 24 of which were critical texts and 48 of which were filler texts. The experiment involved two sessions that were administered two days apart. Half of the critical and filler texts were presented during the first session, and the other half were presented during the second session. Each session began with instructions and a practice text to illustrate the moving window method. The first eight texts presented during experimental trials were filler texts to allow further practice with the moving window before encountering a critical text. The critical

texts and the remaining filler texts for that session were then presented in eight blocks, on the following schedule: Of the twelve critical texts that were presented in that session, four contained unambiguous target sentences and were presented once in each block for a total of eight presentations. Four of the critical texts contained ambiguous target sentences and were also presented once in each block for a total of eight presentations. The remaining four critical texts for that session contained ambiguous target sentences but were only presented once, with one of the four included in Blocks 2, 4, 6, and 8. Finally, each filler text was only presented once, with two new filler texts assigned to each block. The order of text presentation within a block was random, except for the ambiguous texts that were only presented once, which were the last text presented in their block. Assignment of text to condition (unambiguous, repeated ambiguous, or new ambiguous) and to session (first or second) was counterbalanced across participants.

To encourage participants to read carefully, four comprehension questions were written for each critical text, and one comprehension question was written for half of the filler texts. Each question asked whether a short statement about the text was true or false. The comprehension questions for critical texts were presented after every other block (either during even-numbered blocks or during odd-numbered blocks), such that half of the texts in each block were followed by a comprehension question.

Participants and Design

Forty-eight University of Colorado undergraduates participated for course

credit in Introductory Psychology. Data from one participant were lost because of experimenter error. The two within-subject variables were Sentence Type (unambiguous, repeated ambiguous, or new ambiguous) and Study Trial (1-8).

Results and Discussion

In Figure 8, mean reading times (in msec, across participants and sessions) for disambiguating regions in the repeated ambiguous and unambiguous conditions are shown for each study trial. Once again, the signature pattern of automatization is evident in both conditions, with decreasing reading times across trials. Consistent with the prediction of the memory-based processing account, reading times were

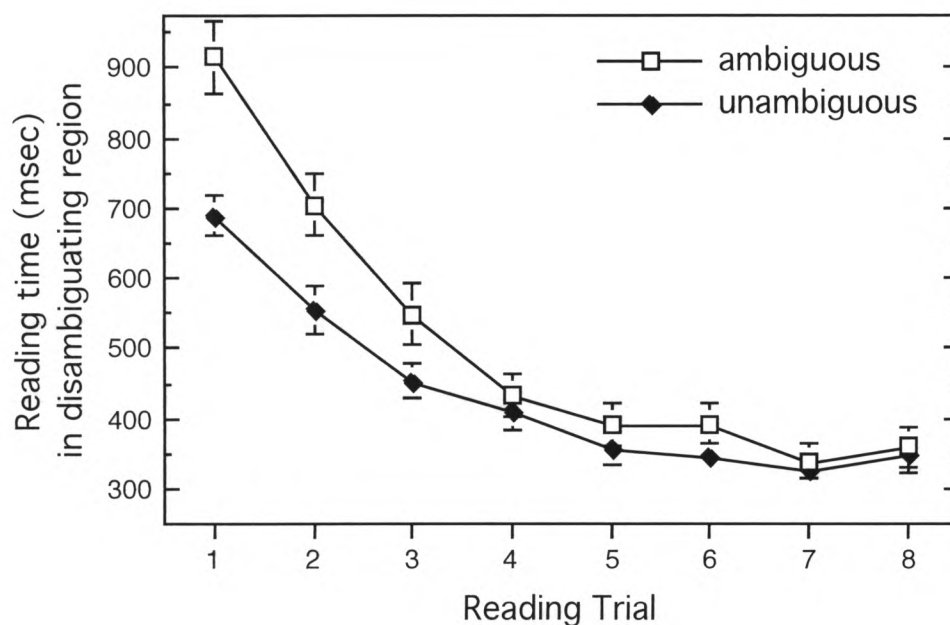


Figure 8. Mean reading times (in msec) for the disambiguation region of ambiguous and unambiguous versions of the target sentences, for each reading trial in Experiment 4. Error bars represent *SEMs*.

greater in the ambiguous condition than in the unambiguous condition during initial study trials, $t(46) > 3.02$ on Trials 1-3, but no longer differed by the final study trials, $ts < 0.73$ on Trials 7-8.

More important, Figure 9 plots mean reading times for the disambiguation region in the 72 experimental trials in which an ambiguous text was presented. The left panel includes the 36 trials in Session 1 and the right panel includes the 36 trials in Session 2. To revisit, in each session, these 36 trials include eight presentations for each of four repeated ambiguous texts and one presentation each for four new ambiguous texts. The numbers along the x-axis group the experimental trials into blocks. For example, Block 1 in each session contains the four experimental trials in which repeated ambiguous texts were first presented (with a different set of texts in each session). Block 2 contains the second presentation of each of these texts, and so on.

First, consider the results bearing on the prediction of the memory-based processing account. In contrast to Experiments 1-3, the repeated texts were presented in distributed rather than massed fashion—each text was presented once in each block, such that filler texts, unambiguous texts, and other ambiguous texts intervened between each presentation of a particular text. Nonetheless, strong item-specific effects were still observed, with processing times on Trial 8 significantly faster than on Trial 1, $t(46) = 12.51$, $p < .01$, and significantly faster than processing time for the new ambiguous text presented at the end of each session, $t(46) = 6.60$, $p < .01$. Given that distributed presentation was used, these effects are most reasonably attributed to retrieval of prior interpretations from long-term memory rather than to temporary maintenance of activation.

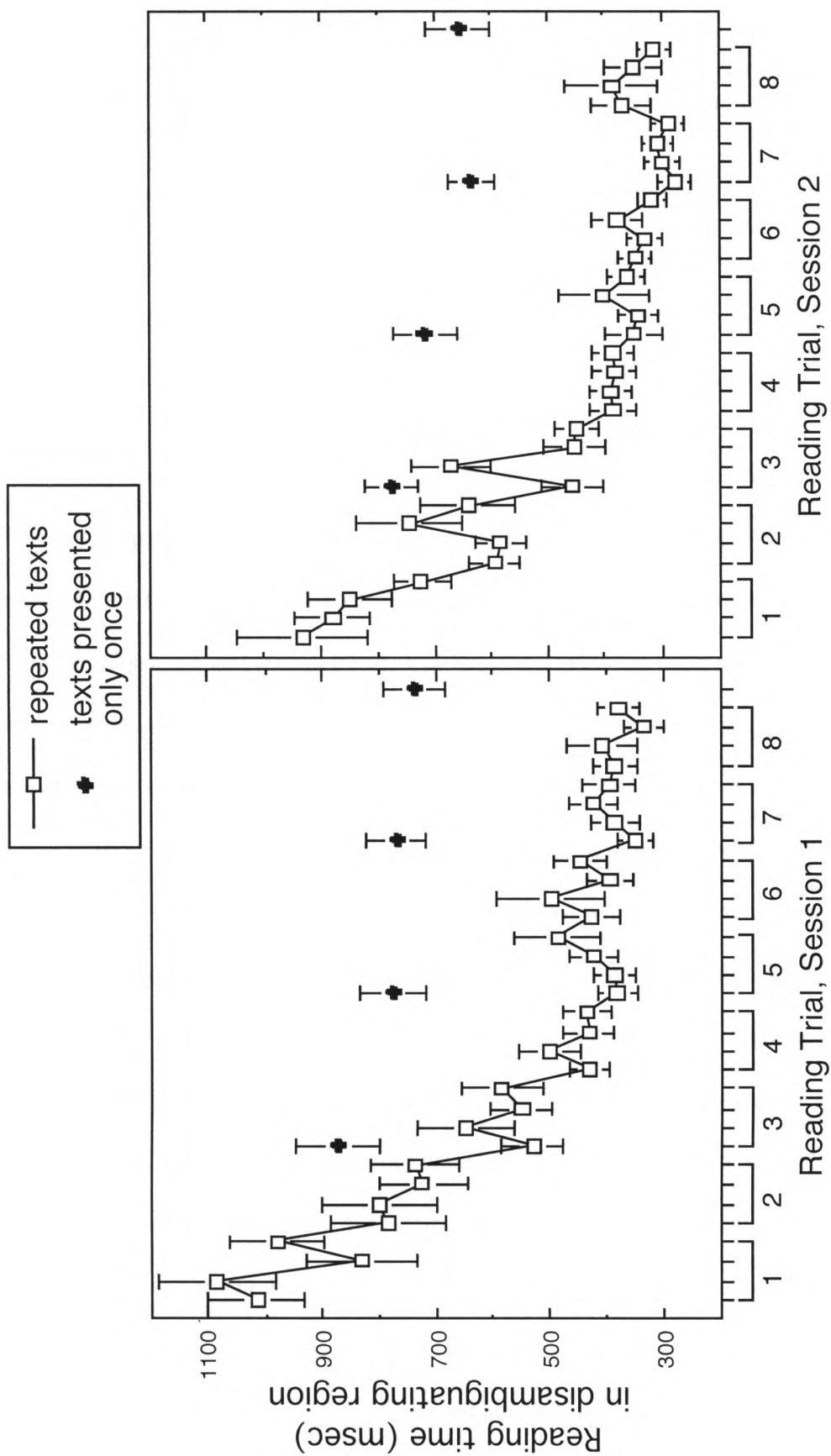


Figure 9. Mean reading times for the disambiguation region in the 72 experimental trials in which an ambiguous text was presented. The left panel includes the 36 trials in Session 1 and the right panel includes the 36 trials in Session 2. In each session, the 36 trials included eight presentations for each of four repeated ambiguous texts and one presentation for each of four new ambiguous texts. The numbers along the x-axis group the experimental trials into blocks. For example, Block 1 in each session contains the four experimental trials in which repeated ambiguous texts were first presented (different texts were used in each session). Block 2 contains the second presentation of each of these texts, and so on. Error bars represent *SEMs*.

With respect to evaluating the potential contribution of computational efficiency, Experiment 4 included 16 trials in which a novel ambiguous text was presented: the first study trial for each of the eight repeated ambiguous texts (four in Block 1 of Session 1 and four in Block 1 of Session 2) plus the eight ambiguous texts that were presented only once. The negative slope from the linear regression over these study trials when the data are plotted in logarithmic coordinates was significant ($-.78, p < .01$). The gains in computational efficiency may not have been completely preserved across the two-day interval between sessions, with reading time somewhat slower for the first ambiguous text in Block 1 of Session 2 than for the last new text presented at the end of Session 1. However, this difference was not significant [$t(46) = 1.66, p = .10$] and reading times for novel texts in Session 2 quickly approached those at the end of Session 1, suggesting that at least some of the initial increase in Session 2 may have reflected warm-up effects (e.g., Anderson, Fincham, & Douglass, 1999). Thus, Experiment 4 provides more conclusive evidence for a potential role of computational efficiency in automatization of text processing and suggests that gains in computational efficiency can be maintained across time and intervening material.

CHAPTER VI

EXPERIMENT 5

Experiment 4 provided evidence that interpretations computed during text processing can be stored in long-term memory and then later retrieved to replace computation on subsequent encounters. This evidence was obtained with distributed presentations, showing that memory-based processing can operate with intervening time and material. Experiment 5 was designed to provide even stronger evidence for the potential role of memory-based processing in the automatization of text comprehension by distributing trials across two sessions, rather than just within sessions. Experiment 5 also allowed further examination of the extent to which gains in computational efficiency are maintained across a delay.

Method

Materials and Procedure

Materials included 76 short narrative texts (the 72 used in Experiment 4 plus four additional filler texts). The experiment involved two sessions that were administered two days apart. Six of the 24 critical texts included unambiguous target sentences and were presented for 10 study trials, five during Session 1 and five during Session 2. Likewise, six of the 24 critical texts included ambiguous target sentences

and were presented for 10 study trials, five during Session 1 and five during Session 2. The remaining 12 critical texts each included an ambiguous target sentence and were presented for only one study trial. Three of these were presented in Session 1 and the other nine were presented during Session 2. Thus, each session included nine trials in which a novel ambiguous text was presented: Session 1 included the first presentation for each of the six repeated ambiguous texts plus three new ambiguous texts, and Session 2 included nine new ambiguous texts. Assignment of text to condition (unambiguous, repeated ambiguous, or new ambiguous) was counterbalanced across participants.

The presentation schedule for the critical texts was somewhat more complicated than in Experiment 4, to more evenly space the introduction of novel ambiguous texts and to provide a better mix of novel and repeated ambiguous text trials (note that in Experiment 1, four of the eight ambiguous texts in each session were introduced in the first block, prior to the repetition of any of those texts). Session 1 began with instructions and a practice text to illustrate the moving window method. The first six texts presented during experimental trials were filler texts to allow further practice with the moving window. The critical texts and the remaining filler texts were then presented in twelve blocks. Six of the blocks (Blocks 1-3 and 6-8) included the introduction of one of the six unambiguous texts and one of the six repeated ambiguous texts. Each of these 12 texts was then repeated in the four blocks following the one in which it was introduced (e.g., if Text A was introduced in Block 3, then Study Trials 2-5 for Text A would be presented in Blocks 4-7). One or two filler texts were also presented in each block. Order of text presentation within a

block was random. One of the three new ambiguous texts (i.e., those presented for only one study trial) was presented in Block 11, in Block 12, and in the last experimental trial of the session (hereafter referred to as Block 13).

Session 2 also began with instructions and then filler texts during the first six experimental trials. Study Trials 6-10 for the repeated texts and the remaining filler texts were then presented in 12 blocks. The sixth study trial for each of the repeated ambiguous and unambiguous texts was presented during the same block number in which it had been introduced in Session 1 (e.g., if the first study trial for Text A had been presented in Block 3 of Session 1, then the sixth study trial for Text A was presented in Block 3 of Session 2). Study Trials 7-10 for each text were then presented in the four blocks following the one in which the sixth study trial was presented. One or two filler texts were also presented in each block, with a random order of text presentation within a block. Finally, one of the nine new ambiguous texts was presented during each of the following blocks: 1-3, 6-8, and 11-13.

Comprehension questions were administered as in Experiment 4.

Participants and Design

Forty-eight University of Colorado undergraduates participated for course credit in Introductory Psychology. Data from one participant who failed to follow directions were excluded from analysis. The two within-subject variables were Sentence Type (unambiguous, repeated ambiguous, or new ambiguous) and Study Trial (1-10).

Results and Discussion

In Figure 10, mean reading times (in msec) for disambiguation regions in the unambiguous and ambiguous-repeating conditions are shown for each study trial. The signature pattern of automatization is again evident in both conditions, with decreasing reading times across trials. Consistent with the prediction of the memory-based processing account, reading times were greater in the ambiguous condition than in the unambiguous condition during Trials 1-3, $t_s(46) > 3.85$, but did not significantly differ on Trials 4-5, $t_s < 1.22$. Reading times diverged somewhat on the sixth study trial (i.e., the first time the repeated items were encountered again in

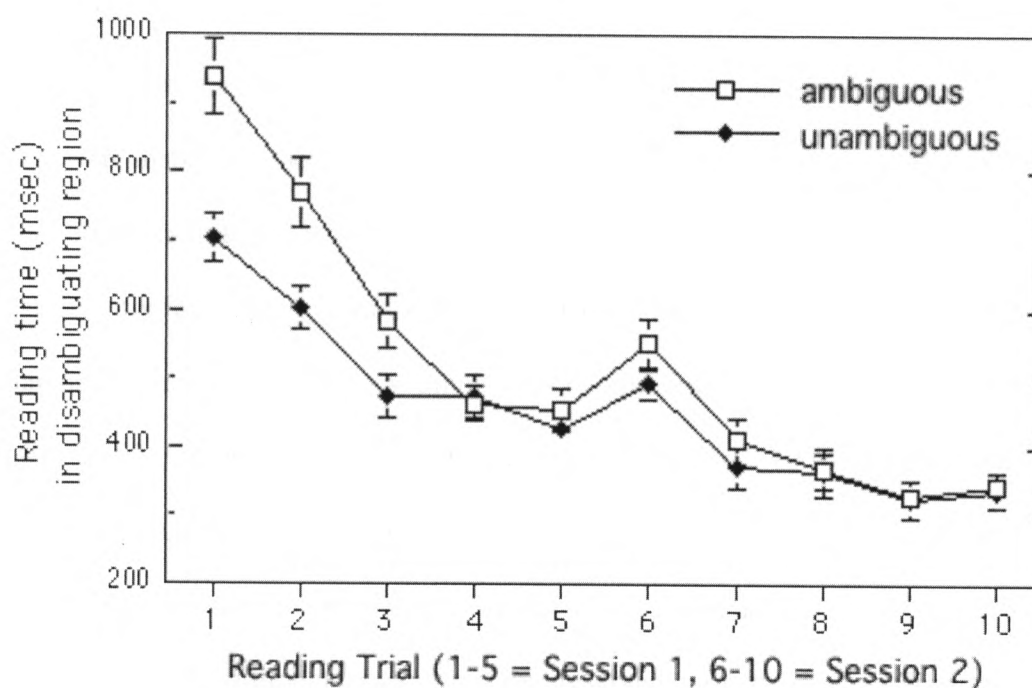


Figure 10. Mean reading times (in msec) for the disambiguation region of ambiguous and unambiguous versions of the target sentences, for each reading trial in Experiment 5. Error bars represent *SEMs*.

Session 2), $t(46) = 2.04, p < .05$, but did not differ significantly on any of the remaining trials, $t_s < 1.23$. Indeed, the numerical difference between reading times in the two conditions on Trials 8-10 were 4 ms, 4 ms, and 6 ms respectively, a point that will be considered further in the General Discussion.

More important, Figure 11 plots mean reading times for the disambiguation region in the 72 trials in which an ambiguous sentence was presented. To revisit, 60 of these 72 trials included 10 presentations of each of the six repeated ambiguous texts. For these texts (each plotted separately in Figure 11), Study Trials 1-5 were presented in Session 1, and Study Trials 6-10 were presented in Session 2. The other 12 of the 72 trials included one presentation for each of the 12 new ambiguous texts, which were spread out across the two sessions.

First, consider the results bearing on the prediction of the memory-based processing account. In contrast to Experiment 4, the presentations of the repeated texts were distributed both within and across sessions. Strong item-specific effects were observed in both sessions. Across texts, reading times on Study Trial 5 were significantly faster than on Study Trial 1, $t(46) = 9.45, p < .01$, and significantly faster than processing time for the new ambiguous text presented in Block 13 of Session 1, $t(46) = 6.52, p < .01$. Similarly, reading times on Study Trial 10 were significantly faster than on Study Trial 6, $t(46) = 6.80, p < .01$, and significantly faster than reading time for the new ambiguous text presented in Block 13 of Session 2, $t(46) = 7.70, p < .01$. Additionally, although not completely preserved, item-specific effects were evident across the two-day interval between the sessions. Although reading times were significantly longer on Study Trial 6 than on Study Trial 5, $t(46) = 2.48, p < .02$,

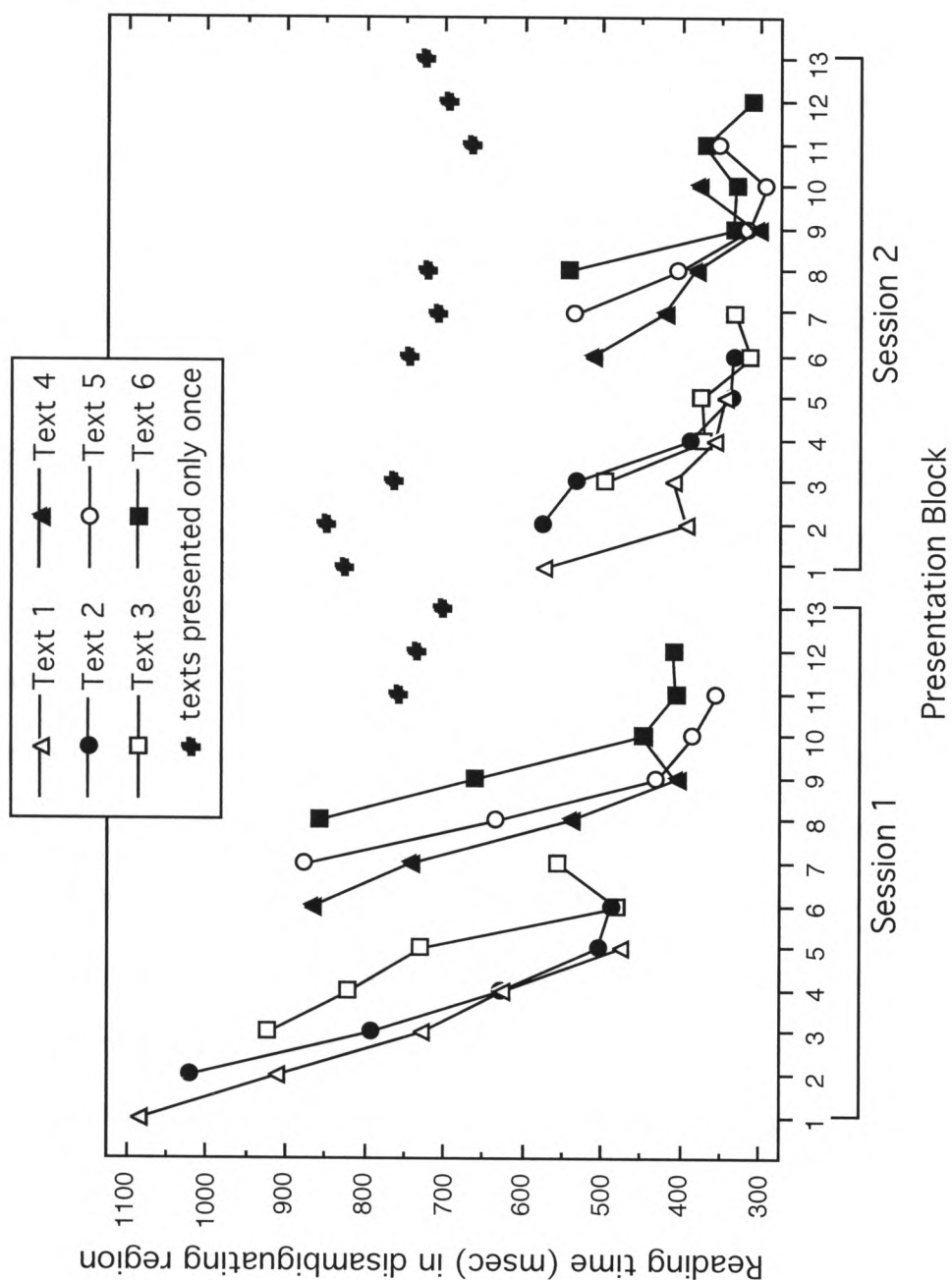


Figure 11. Mean reading times (in msec) for the disambiguation region in the 72 trials in which an ambiguous sentence was presented. Sixty of these 72 trials included 10 presentations for each of six repeated ambiguous texts. For each of these texts, Study Trials 1-5 were presented in Session 1, and Study Trials 6-10 were presented in Session 2. The other 12 of the 72 trials included one presentation for each of 12 new ambiguous texts, which were spread out across the two sessions. Error bars were not included in this figure to improve the legibility of the data for the repeated texts.

Study Trial 6 was significantly faster than Study Trial 1, $t(46) = 8.30, p < .01$.

Furthermore, reading times in Session 2 quickly matched those observed at the end of Session 1, suggesting that at least some of the increase on Study Trial 6 may have been due to warm-up effects.

With respect to evaluating the potential contribution of computational efficiency, Experiment 5 included 18 trials in which a novel ambiguous text was presented: the first study trial for each of the six repeated ambiguous texts (one in each of Blocks 1-3 and 6-8 in Session 1) plus the 12 ambiguous texts that were presented only once. The negative slope from the linear regression over these study trials when the data are plotted in logarithmic coordinates was significant ($-.93, p < .01$). As in Experiment 4, the gains in computational efficiency may not have been completely preserved across the two-day interval between sessions, with reading time somewhat slower for the first novel ambiguous text in Session 2 than for the last novel text presented in Session 1. However, this difference was not significant [$t(46) < 0.55$]. Thus, Experiment 5 provides further evidence for a role of computational efficiency in automatization of text processing, showing again that gains in computational efficiency can be maintained across time and intervening material.

CHAPTER VII

GENERAL DISCUSSION

A major goal of the current work was to motivate closer examination of automaticity in text processing theory and research, as automaticity is a core but ill-defined concept within the area. The present research also represents one of the first empirical studies specifically designed to explore the nature of the processes that may underlie automatization in text comprehension. Specifically, the research evaluated two processing mechanisms derived from basic theories of automaticity in the content of text processing, a memory-based processing mechanism and a computational efficiency mechanism. Below, the results bearing on the potential role of these two mechanisms in automatization of text processing are discussed, and then the broader significance of this research is briefly considered.

Evidence for Memory-Based Processing

Several outcomes converge on the conclusion that memory-based processing contributed to the speed-up with practice observed in the present experiments. First, examination of the pattern of reading times across all encounters of ambiguous sentences (Figures 2, 5, 7, 9, and 11) revealed a high degree of item-specificity in the

reading time improvements that accrued with practice.⁷ Whereas repeated items enjoyed substantial gains in reading speed across presentations, by comparison, more modest improvements were evident for initial encounters of novel items. According to the memory-based processing account, this item-specific speed-up reflects a shift to retrieval of previously computed interpretations for those repeated items, which does not extend to novel items for which no prior interpretations have been stored. Second, Experiments 1, 2, 4, and 5 demonstrated that whereas reading times were longer for ambiguous sentences than for unambiguous sentences on initial processing trials, reading times no longer differed significantly by the final processing trials. According to the memory-based processing account, this convergence was due to different computational processes underlying performance in the two conditions on initial trials but the same memory-based process supporting performance in both conditions by the final trials. Third, Experiment 3 demonstrated an increase in reading times when the syntactic structure of target sentences was changed from a structure that is generally less preferred to one that is generally highly preferred during initial interpretation (i.e., a “reverse” garden-path effect). The memory-based processing account easily explains the observed pattern: On initial trials in which the less preferred interpretation is in fact correct, readers initially adopt the incorrect interpretation but then subsequently reanalyze and store the correct, less-preferred

⁷ The item-specific benefit of repetition may appear to contrast with research that has examined syntactic priming (i.e., processing of a phrase with a particular syntactic structure facilitates the processing of a subsequent phrase with the same structure). However, most research on syntactic priming has explored the effect in language production rather than comprehension (Branigan, Pickering, Liversedge, Stewart, & Urbach, 1995). The effect in comprehension is not well established, and the extent to which syntactic priming in comprehension would persist across time or intervening material (as in the present research) is unknown.

interpretation. These less-preferred interpretations are then accessed via direct retrieval on subsequent encounters of the item. On the final trial in which the syntactic structure of the sentence has been altered, the less-preferred interpretation is no longer appropriate, thus resulting in an elevation of reading times.

In sum, the memory-based processing account provides a straightforward explanation of (a) item-specific practice effects, (b) the convergence of reading times in the ambiguous and unambiguous conditions, and (c) the reverse garden-path effect. However, one relatively consistent finding that the memory-based processing account cannot explain is the item-general practice effects. This is not to say that the theories proposing the particular memory-based mechanism examined here could not account for item-general effects—indeed, CMPL assumes that an algorithm can accrue strength on those trials in which it is executed, and a similar assumption could be incorporated into Instance Theory to increase its generality. Rather, the important point is that the memory-based mechanism cannot solely account for the effects observed here, suggesting that at least one other mechanism is involved.

Evidence for Computational Efficiency

In contrast to the memory-based processing account, the computational efficiency account provides a straightforward explanation of the significant item-general practice effects found in four of the five experiments (the trend was not significant in Experiment 2 but was in the expected direction). Returning to the ACT Theory that motivated the formulation of the particular computational efficiency account examined here, we can speculate about how these item-general affects may

have arisen. One possibility is that the initial ambiguous sentences may have been treated as problems to which domain-general interpretive processes were applied, resulting in the compilation of domain-specific productions for reanalyzing misinterpreted sentences. These more efficient compiled productions may then have been used on subsequent encounters of ambiguous sentences. On one hand, this possibility is not entirely implausible, given that these ambiguous sentences are often quite difficult to reanalyze. On the other hand, most if not all undergraduate readers will have encountered ambiguous sentences previously and thus presumably would already have domain-specific productions available to correct misinterpretations. The more plausible possibilities are that compilation processes further reduced the number of steps involved in the reanalysis productions, or that those productions were executed more quickly because they were increasingly strengthened due to recent and frequent execution. The important point is that a gain in computational efficiency (from one or more of these sources) provides a straightforward account of the item-general practice effects.

In contrast, other key findings are not as readily attributed to a computational efficiency mechanism. For example, the computational efficiency account does not provide a straightforward explanation for the convergence of reading times in the ambiguous and unambiguous conditions across trials, although one may be formulated if additional assumptions are made. If one assumes that efficiency gains were substantially greater for reanalysis processes than for analysis processes, one would expect diminishing differences in processing times between the ambiguous and unambiguous conditions. However, a difference on all trials would still be predicted,

given that ambiguous sentences would continue to require reanalysis. Indeed, although not significant, a numerical difference in processing times between the two conditions was evident on Trial 4 in Experiments 1 and 2 (19 and 15 msec, respectively). However, the difference further diminished in Experiment 5 to 4-6 ms on Trials 8-10. Even allowing for measurement error, it is debatable whether reanalysis could be accomplished in this amount of time (by way of comparison, ACT assumes that productions are executed serially and require a minimum of 50 ms each).

The computational efficiency account also does not provide a straightforward explanation for the increase in reading times on Trial 4 when target sentences were altered in Experiment 3. The garden path effect on Trial 1 suggests that initial processing of the ambiguous sentences involved adoption of the preferred main-verb interpretation initially (and then subsequent reanalysis based on disambiguating information). On Trial 4, the main-verb interpretation is in fact correct. If the underlying basis for interpretation was still computation (albeit improved in efficiency), the main-verb interpretation would still have been adopted initially. It is unclear why processing time would increase upon encounter of information now consistent with the interpretation provided by that computation.

In sum, the item-general practice effects are most easily attributed to a computational efficiency mechanism, suggesting a potential role for computational efficiency in the automatization of text processing. However, the computational efficiency account does not easily explain the convergence of reading times in the ambiguous and unambiguous conditions, and the reverse garden-path effect observed

in Experiment 3. As formulated here, the computational efficiency account also does not explain the item-specific benefits of practice above and beyond the item-general effects. This is not to say that the ACT Theory proposing the particular computational efficiency mechanism examined here could not account for the item-specific effects—indeed, in a recent version of ACT (Anderson & Lebiere, 1998), a mechanism for retrieval of specific prior solutions is explicitly incorporated into the model. The important point is that the computational efficiency mechanisms proposed by the theory cannot be the only contributors to the speed-ups with practice observed here. Consistent with this conclusion, Blessing and Anderson (1996) state that “we judge as implausible any theory that attributes skill acquisition to a single learning mechanism” (p. 945).

Potential Role of Memory-Based Processing and Computational Efficiency in Automaticity of Text Processing

Memory-based processing and computational efficiency may both play a role in automaticity in text processing. The present research provided evidence that each of these non-exclusive mechanisms can contribute to speed-ups with practice in text processing. Of course, the mechanisms were only evaluated in the context of one of the component processes involved in text comprehension (syntactic parsing). Thus, an important question must be considered: To what extent might either of these mechanisms support automatization in text processing more generally?

Obviously, one important direction for future research will be to extend the present findings to other text processing situations and materials. Additionally, given

the consensus that not all mechanisms contribute to automaticity in all tasks or processing situations, it will be important to establish the viability of these mechanisms as bases for automatization of other component processes involved in text comprehension. Another factor that merits further research concerns the time intervals over which each of these mechanisms may operate. The results of Experiments 4-5 are somewhat encouraging with respect to this issue, showing that both memory-based processing and computational efficiency can contribute to gains in processing speed even with intervening material and over at least 48-hour intervals between items. Nonetheless, future research that further explored the temporal characteristics of these mechanisms in text processing would be valuable.

At least two other factors must be considered when evaluating the potential contribution of these mechanisms to automaticity in text processing. First, evidence for both computational efficiency and memory-based processing was observed after a relatively small number of trials. In contrast, some researchers have suggested that automaticity requires a great deal of practice to develop, with thousands of trials administered in some tasks. Do the present results reflect automatization, given the small numbers of trials involved? And more generally, can these mechanisms contribute to automaticity in text processing, given the relatively small number of times an item may repeat in natural text? The inconsistency between the number of trials necessary to demonstrate automatization in the present research and in previous research may be more apparent than real. Part of the apparent inconsistency is due to the use of different criteria. For example, Schneider and Shiffrin (1977) administered 4300 trials in a visual search task. However, their goal was to train participants to

reach asymptotic performance. By contrast, according to Instance Theory, performance is defined as automatic when it is based on retrieval of prior interpretations. In principle, performance can be “automatic” after one exposure to an item, provided that the interpretation of that item is stored and can subsequently be retrieved quickly enough to outperform computational processes. According to this account, the rapidity with which automaticity can be achieved would be determined by memory-related factors (e.g., interference from the similarity of other items, factors influencing the memorability of the target items) rather than the number of exposures per se. Consistent with this account and with the present results, Logan and colleagues have shown negatively accelerated speed-ups in some tasks with less than 15 minutes of training or with as few as 10-16 repetitions (Grant & Logan, 1993; Logan, 1990; Logan & Klapp, 1991).

Second, the question about the requisite number of trials for automaticity points to a closely related factor that must be considered when evaluating the potential contribution of these mechanisms to automaticity in text processing: How often computational processes are executed and how often specific items repeat in “natural” text (for present purposes, the kinds of texts that readers are typically reading outside of experimental contexts) depends upon the grain size at which an “item” is defined. Here, a very coarse grain of item repetition was used—paragraph-length texts were repeated across the experiment (given that this research represented the first attempt to directly investigate process accounts of automaticity, this strong manipulation was used to ensure that practice effects would obtain). Of course, seldom will full paragraphs repeat in natural text, outside of a reader’s decision to

revisit previously read text. Indeed, seldom will complete sentences repeat (direct quotes in expository text notwithstanding).

However, a role for computational efficiency and memory-based mechanisms in automatization of text processing is still quite plausible when one considers that many items repeat in natural text when a finer unit of analysis is considered. Much of the information within texts repeats at grain sizes below the sentence-level unit (e.g., phonemes and morphemes, words, concepts, syntactic phrase and clause structures, connectives, semantic propositions, simple facts, idioms). Although much less frequent, repetition at grain sizes above the sentence-level unit are also possible (e.g., schemas for common events and situations, Sanford & Garrod, 1998). Some of these forms of repetition may be more or less advantageous for developing computational efficiency or for supporting memory-based processing. For example, with respect to the computational efficiency account, basic syntactic structures repeat thousands of times in an average adult reader's exposure to print. The fact that these structures will include many different nouns and verbs is not problematic for the computational efficiency account, given that its primary contribution to improvements with practice is in the speed with which item-general computations can be executed.

What about the memory-based processing mechanism, given that its primary contribution to improvements with practice is in the speed with which specific items can be processed? The unit of analysis for memory-based processing would thus appear to be much more severely constrained than it is with computational efficiency. Although the frequency with which specific tokens repeat is necessarily less than the frequency with which types repeat, tokens at several grain sizes repeat frequently

enough to still allow a plausible role for memory-based processing. Almost all words repeat tens, hundreds, or thousands of times in an average adult reader's exposure to print. Furthermore, some findings in the extant literature on syntactic parsing implicate the retrieval of item-specific interpretive information. For example, Garnsey, Pearlmutter, Myers, and Lotocky (1997) presented readers with sentences that contained ambiguous verbs, as in the present research. Important for present purposes, some of the verbs were biased toward a main verb interpretation (i.e., in a norming study in which individuals were asked to generate sentence completions for each verb, the verbs were followed about five times more frequently by a direct object than by a subordinate clause), whereas some of the verbs were biased toward the typically less-preferred subordinate clause interpretation. When the ambiguous verbs were presented in sentences in which they participated in a subordinate clause (as in the materials used here), reading times in the disambiguating region were elevated for those verbs with a main-verb bias but not for those with a subordinate-clause bias. Presumably, for these latter verbs, the subordinate-clause interpretation had been adopted initially and thus no reanalysis was necessary at the point of disambiguation. If so, this suggests that item-specific information about the particular verbs had been retrieved to support initial interpretation. Finally, as Logan (1997) has argued,

The single-trial learning in the instance theory allows automatization to occur at every level. All that is required, in principle, is one repetition, and even high-level structures may repeat themselves once. Automaticity may never become particularly strong at higher levels because the low frequency of repetition limits the number of traces in memory, but initial gains are strongest, and some benefits of automaticity may be apparent at every level. (14)

The memory-based processing account also complements a memory-based view of text processing that has recently emerged in the literature (e.g., McKoon & Ratcliff, 1998; Myers & O'Brien, 1998). McKoon and Ratcliff (1998) have described this view as "the idea that a text's words, concepts, and propositions are understood in terms of the information they evoke from memory" (p. 30), through a direct-access form of retrieval referred to as resonance. They note, however, that "we currently know almost nothing about the boundaries between resonance and other comprehension processes. Delineating the tasks served by memory from other, more constructive processes is an important task for future research" (p. 34). The present research illustrates how the memory-based processing account of automaticity may be particularly valuable in meeting this goal and offers basic methodological approaches that can be used in subsequent investigations.

To summarize, the present research provides important initial evidence that both computational efficiency and memory-based processing may contribute to automatization in text processing. It also highlights critical issues with respect to the potential role of these mechanisms in the processing of natural text. Importantly, each of the issues addressed above (i.e., extension to other component text processes and materials, temporal characteristics, number of repetitions, and unit of analysis) are empirically tractable. Thus, the present work delineates important dimensions that can be systematically evaluated in future research.

Broader Issues and Implications

By synthesizing basic theoretical accounts of automaticity with text processing research, the present work contributes to both domains. The research demonstrates that theories of automaticity can be extended to domains of research involving more complex cognitive tasks than are typically examined by basic automaticity research. As Lee and Anderson (2001) have noted, most basic automaticity and skill acquisition theories “have had considerable success in addressing the fine details of learning relatively simple tasks. While encouraging, these demonstrations leave the worry that there may be problems with scaling up to the complex tasks that are more typical of human learning in the real world. A challenge to the learning theories is whether they can provide a complete characterization of the acquisition of truly complex skills” (p. 268). The present research provides tentative evidence that basic theories of automaticity will indeed scale up to more complex tasks.

This research contributes to the text processing domain by recommending an important advance in the conceptualization of automaticity, a central concept in many text comprehension theories. Specifically, conceptualizing automaticity in terms of the underlying cognitive processes promises a more fruitful approach to understanding automaticity than does the more typical property-list approach. For example, conceptualizing automaticity in terms of underlying processes can guide research toward questions that will further our understanding of text processes. Whereas defining automaticity in terms of observable properties motivates descriptive “when” questions (e.g., “When are ‘automatic’ elaborative inferences

made?”), conceptualizing automaticity in terms of underlying processes motivates explanatory “why” questions and suggests hypotheses that can be evaluated empirically.

Of course, only two of many possible instantiations of process accounts were evaluated in the present work, and other viable process accounts of automaticity in text comprehension will merit evaluation in future research. Nonetheless, to the extent that this initial research motivates healthy theoretical debate and further empirical investigation of automaticity in text processing, the highest-level goal of this work will have been met.

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